云南武定迤纳厂 Fe-Cu-REE 矿床的锆石 U-Pb 和黄铜矿 Re-Os 年代学、稀土元素地球化学及其地质意义*

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Ye XT, Zhu WG, Zhong H, He DF, Ren T, Bai ZJ, Fan HP and Hu WJ. 2013. Zircon U-Pb and chalcopyrite Re-Os geochronology, REE geochemistry of the Yinachang Fe-Cu-REE deposit in Yunnan Province and its geological significance. *Acta Petrologica Sinica*, 29(4):1167-1186

Abstract The Yinachang Fe-Cu-REE ore deposit is hosted in the Paleoproterozoic Yinachang Formation of the Lower Kunyang Group in the Kangdian iron-copper metallogenic province SW China. The main minerals in the Yinachang ore bodies consist of chalcopyrite magnetite quartz and calcite. As the host rocks of the deposit had experienced intensively alternation and metamorphism the age and origin of the Yinachang deposit are still a matter of hot debate. U-Pb ages of detrital zircons from the volcanic tuff and breccia in the Yinachang Formation have been used to identify the provenance and evaluate the age of the Yinachang Formation of the Lower Kunyang Group. Most analyzed zircon grains show oscillatory zoning and have high Th/U ratios >0.4 suggesting that they were mainly derived from igneous rocks. A total amounts of about 200 detrital zircons exhibit U-Pb age populations at 1.75 ~ 1.88Ga 1.90 ~ 2.00Ga 2.02 ~ 2.20Ga and 2.30 ~ 2.40Ga with the oldest $^{207}Pb/^{206}Pb$ age of ~3.0Ga and the youngest age of ca. 1750Ma. The dating results provide a maximum deposition age of ca. 1.7Ga for the Yinachang Formation and suggest the possible existence of older basement. Rhenium-osmium dating for six chalcopyrite samples from the Yinachang Fe-Cu-REE deposit was conducted to constrain the timing of sulfide mineralization. Direct Re-Os dating for chalcopyrite of ore minerals yields an isochron age of 1690 ± 99Ma MSWD = 9.0 and a weighted mean of 1685 ± 37Ma MSWD = 3.0 respectively indicating the main ore-forming age of about 1.7Ga. In addition the major ore types exhibit significantly positive Eu anomaly and LREE enrichment similar to those of modern submarine hydrothermal fluids. The above dating results reveal that the ore-forming age of the deposit is nearly contemporaneous with the deposition timing of the Yinachang Formation and the characteristics of fluid deduced from REE indicate that the ore formation was related to submarine hydrothermal fluids activity. It is therefore suggested that the Yinachang Fe-Cu-REE deposit is a volcanic exhalation-hydrothermal sedimentary deposit. Several recent studies showed the occurrence of relatively widespread magmatism at ca. 1.7Ga and large numbers of synchronous Fe-Cu deposits suggesting that the magmatism is probably the crucial factor for the formation of deposits in this region. Furthermore the Fe-Cu deposits in the Kangdian region may be related to the break-up of the Columbia supercontinent at about 1.7Ga.

Key words Fe-Cu-REE ore deposit Zircon U-Pb dating Chalcopyrite Re-Os dating REE geochemistry Yinachang Yunnan

摘 要 - - й ˝ ,

ˇ й ˊ ˊ ˇ

й ɹ LA-ICP-MS U-Pb

й Th/U ي ˝ >0.4ˌ ˇ 200

^{207}Pb/^{206}Pb Ḇ.75~1.88Gaˇ 1.90~2.00Gaˇ 2.02~2.20Ga 2.30~2.40Gaˇ 3.0Ga

ˇ 1750Ma й 1.7Gaˇ

й Re-Os ˇ й 6 Re-Os

1690±99Ma˝ MSWD=9.0ˌ ˇ 1685±37Ma˝ MSWD=3.0ˌ ˇ

1.7Ga й ˇ ˇ й

ˇ REE й ǐ

- й ˇ 1.7Ga -

ˇ - ˇ 1.7Ga Columbia

й

关键词 - - ḇ U-Pb ḇ Re-Os ḇ ḇ ḇ

中图法分类号 P595 P597.3 P611

al. 2002

1

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1996 IOCG iron oxide-copper-gold

Greentree 2007 Zhao 2010 Zhao and Zhou 2011 -

- 2004

2004 2005 Greentree and Li 2008 Zhao *et al.* 2010 Zhao and Zhou 2011 Zhao *et al.* 2012 Chen and Zhou 2012

- 1.7Ga

-

2008 2009 Greentree and Li 2008 Zhao and Zhou 2011 Chen and Zhou 2012

-

1997

1984 1990 1993 1993

1997 1999 2001

-

Fe-Cu-REE

LA-ICP-MS U-Pb

Re-Os

-

1.7Ga

Columbia Rogers and Santosh 2002 Zhao *et* al. 2002

2

1

-

Greentree and Li 2008

Zhao *et al.* 2010

2009

1990 Hu *et al.* 1991 -

U-Pb

1687±8Ma 2008 1675±8Ma Greentree and Li 2008 1659±16Ma Zhao and Zhou 2011

-

2009 2011

U-Pb 1695±20Ma 2009

1990 2009

Zhao *et al.* 2010

2

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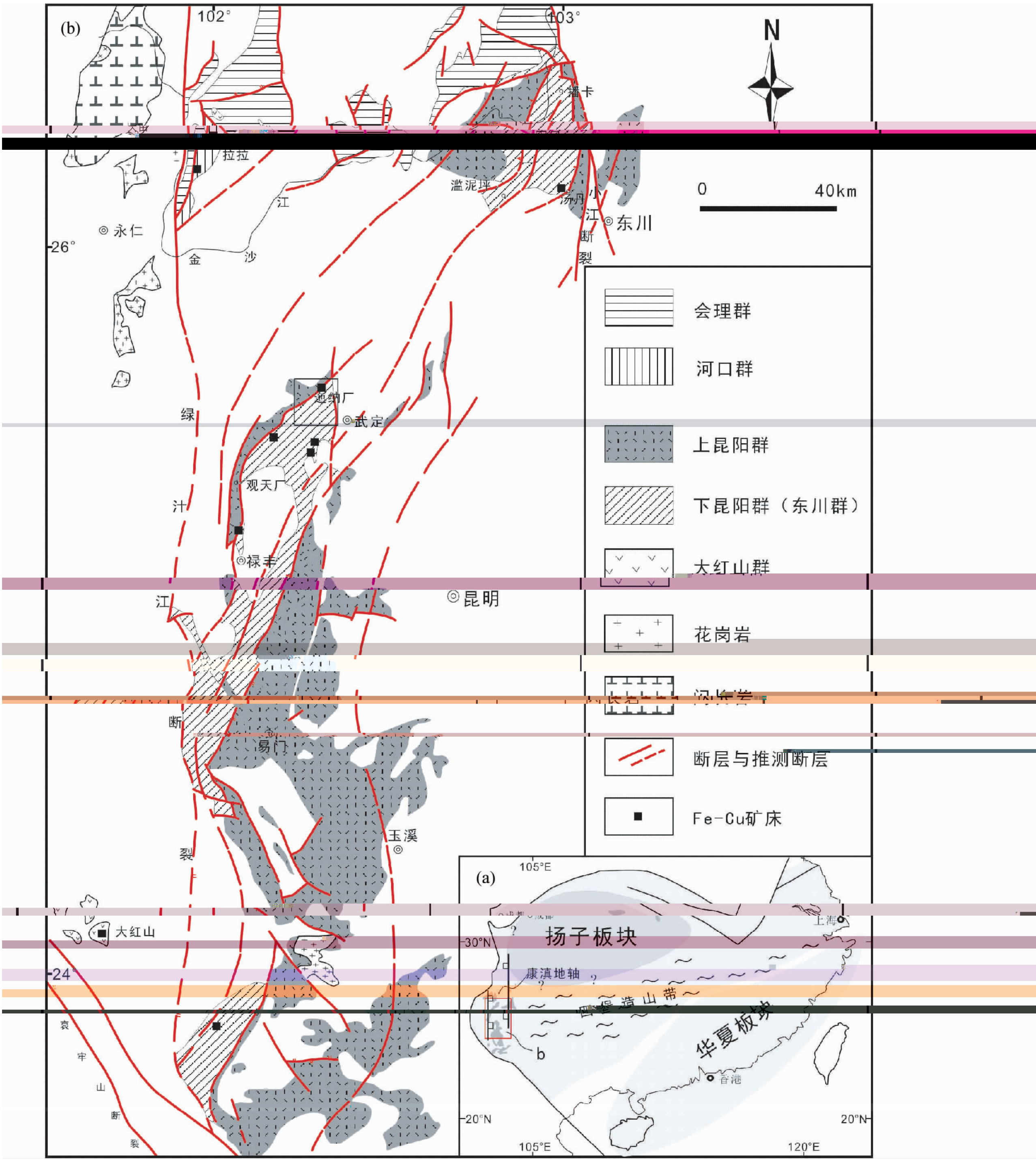
-

U-Pb 1742±13Ma Zhao *et al.* 2010 U-Pb 1690±32Ma Zhao *et al.* 2010 1.7Ga

-

Pb-Pb



1 a Li *et al.* 1999 2002

b 1990

Fig. 1 Simplified tectonic map showing the study area in relation to South China 's major tectonic units a after Li *et al.* 1999 2002 and distribution of the Kunyang Group Dahongshan Group Hekou Group Huili Group and or its equivalents and Fe-Cu deposits in the Kangdian region b after Wu *et al.* 1990

1716 ± 56Ma 1997 1. 8 ~ 1. 5Ga

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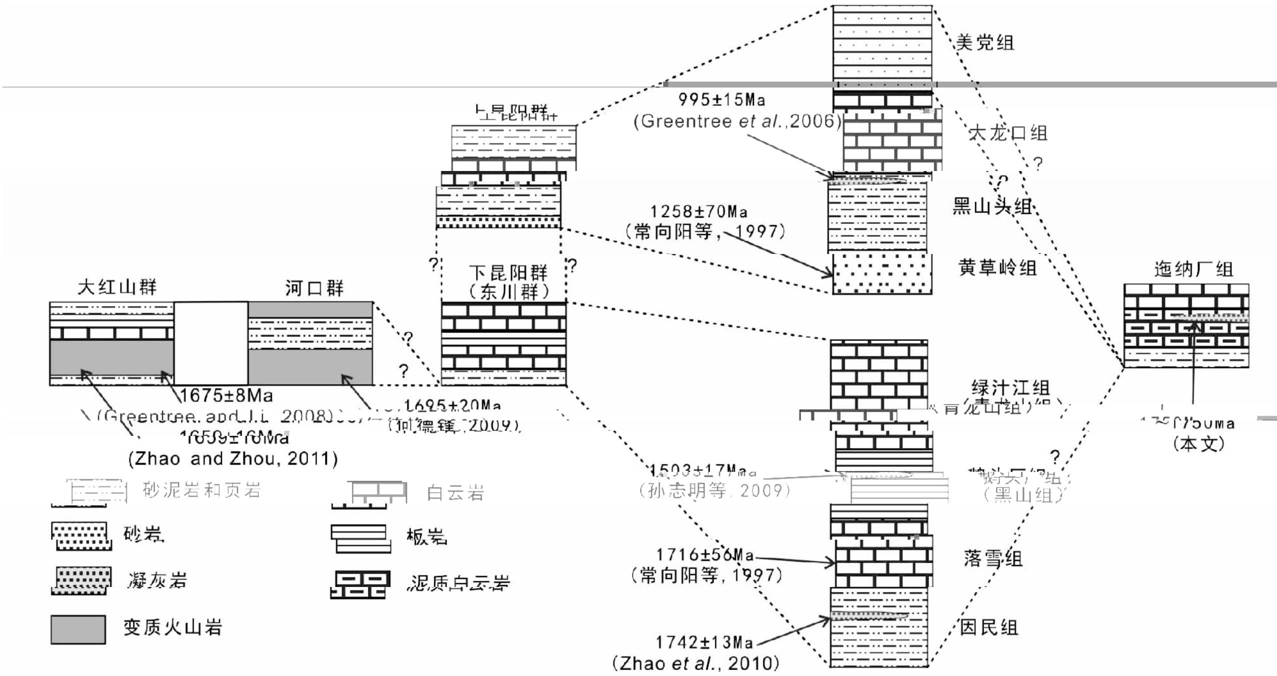
SHRIMP 1503 ± 17Ma 2009 SHRIMP U-Pb 995 ± 15Ma Greentree *et G*



2 Zhao and Zhou 2011

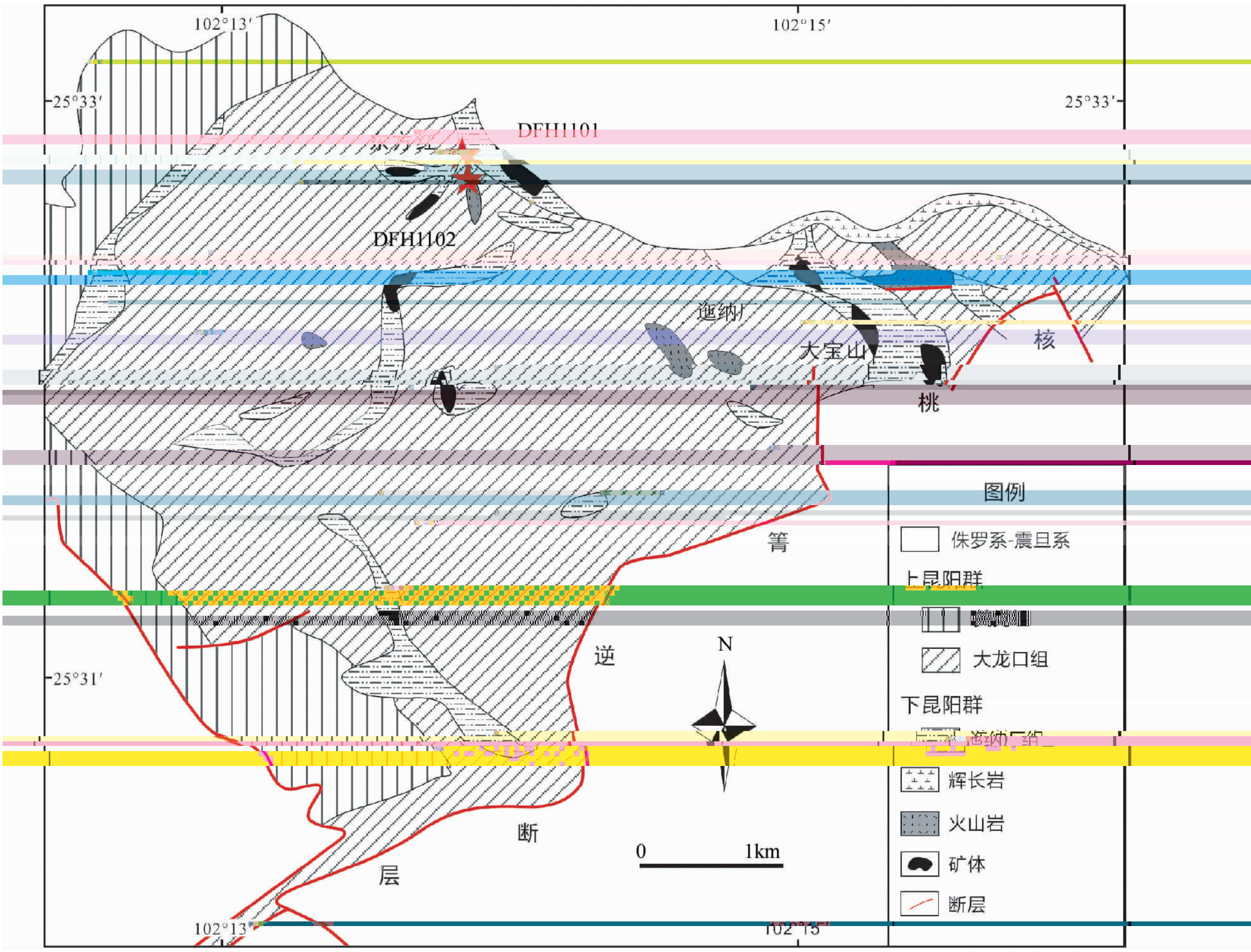
Fig. 2 Stratigraphic sequences of Kunyang Group in the Kangdian region after Zhao and Zhou 2011

1032 ±9Ma 2007

1.8 ~1.0Ga

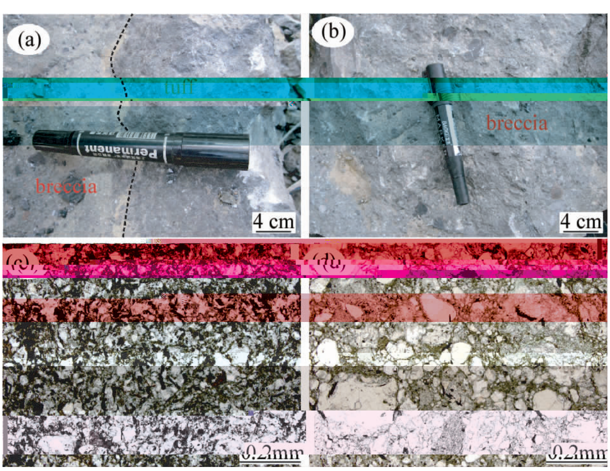
3

Fe-Cu-REE



3 1990

Fig. 3 Simplified geological map of the Yinachang deposit in Wuding County Yunnan Province after Wu *et al.* 1990



4

a - DFH1101 b - DFH1102

c - d -

. tuff- breccia-

Fig. 4 Photographs and photomicrographs of the representative tuff a c and breccias b d from the Yinachang deposit

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LA-ICP-MS U-Pb

DFH1101 N 25°32′53.1″ E 102°13′34.3″

DFH1102 N 25°32′53.1″ E 102°13′34.3″

CL

U-Pb

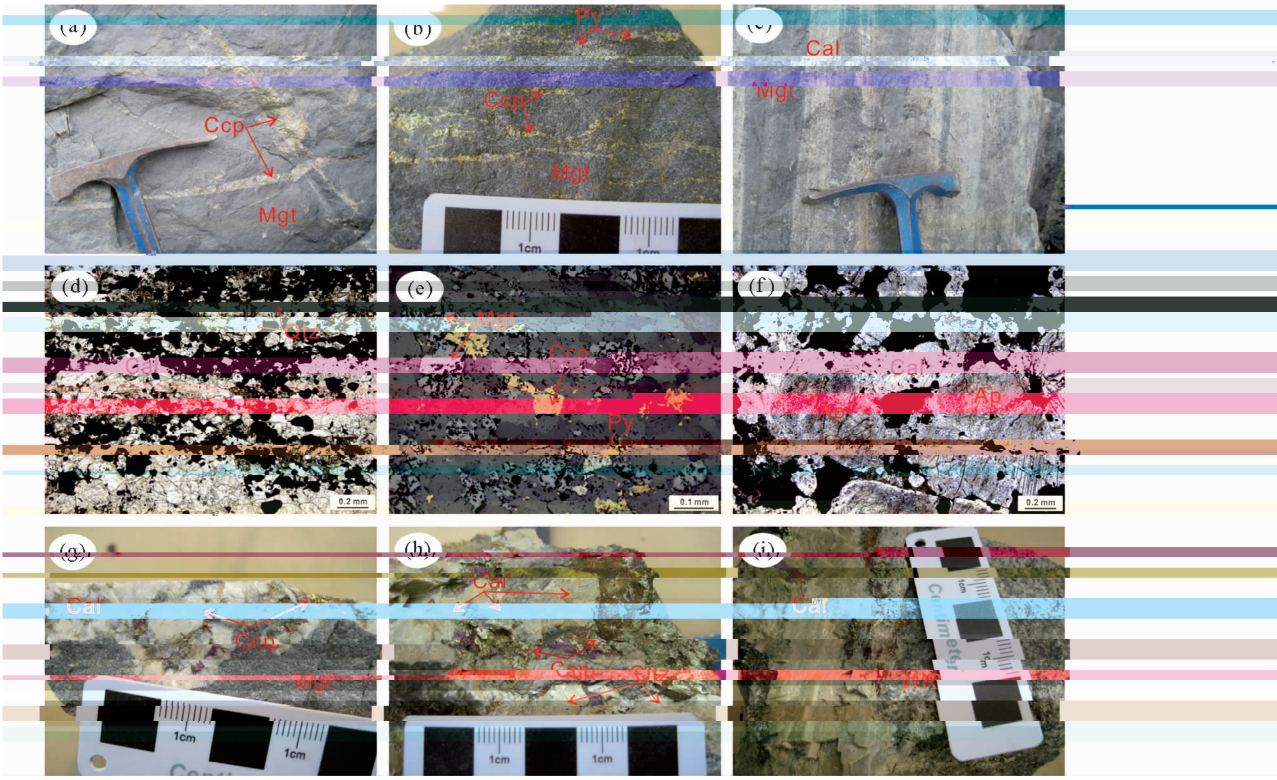
Lamda Physik

GeoLasPro ICP-MS

Agilent 7700x

10J/cm^2

32μm 5Hz 40s

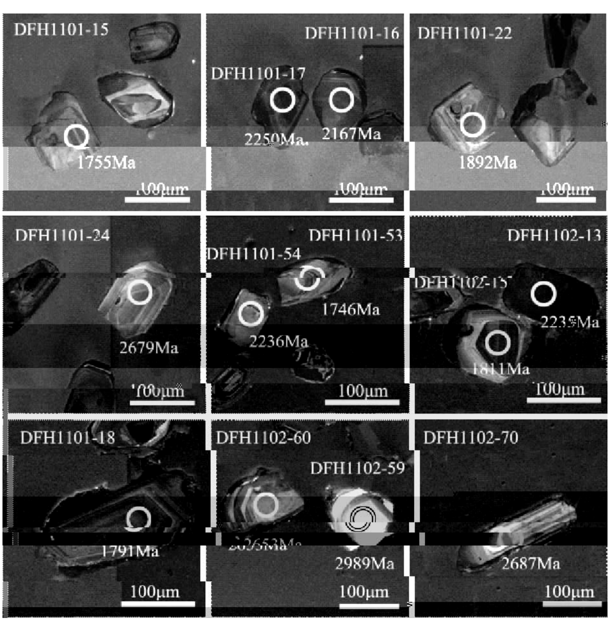


5

a b - c d - e - f - g - h -
i - . Ccp- Cal- Py- Mgt- Ap- Qtz- WR-

Fig. 5 Photographs and photomicrographs of iron-copper ore from the Yinachang deposit

a b -vein-type ore c d -bedded ore e -disseminated ore f -apatite and calcite in the ore g -calcite in the magnetite ore h -calcite in the copper ore i -calcite in the wall-rock. Ccp-chalcopyrite Cal-calcite Py-pyrite Mgt-magnetite Ap-apatite Qtz-quartz WR-wall-rock



6

Fig. 6 Representative CL images of the detrital zircon grains for tuff and breccia from the Yinachang deposit

ICP-MS 91500 GJ-1 Plešovice U-Pb NIST SRM 610 Si Pb Zr Liu *et al.* 2010a Hu *et al.* 2011 ICPMSDataCal Liu *et al.* 2010a b

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表 1　凝灰岩和火山角砾岩的

续表 1

Continued Table 1

	×10⁻⁶			Th/U							Ma						
	Pb	Th	U		$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ	$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ	
-36	80.9	209	142	1.47	0.1200	0.0013	6.3927	0.0761	0.3834	0.0029	1967	19	2031	10	2092	14	97%
-37	87.2	64.5	167	0.39	0.1413	0.0014	8.6286	0.0934	0.4396	0.0030	2243	18	2300	10	2349	13	97%
-38	266.3	264	713	0.37	0.1105	0.0011	5.0255	0.0526	0.3267	0.0018	1809	19	1824	9	1822	9	99%
-39	101.1	93.2	236	0.39	0.1188	0.0014	6.0271	0.0729	0.3643	0.0026	1939	21	1980	11	2002	12	98%
-40	103.0	84.7	196	0.43	0.1444	0.0018	8.8538	0.1100	0.4396	0.0031	2280	21	2323	11	2349	14	98%
-41	69.0	74.6	135	0.55	0.1341	0.0016	7.6710	0.0938	0.4103	0.0030	2154	20	2193	11	2216	13	98%
-42	88.9	142	212	0.67	0.1095	0.0012	5.1544	0.0604	0.3375	0.0023	1792	20	1845	10	1875	11	98%
-43	89.6	89.3	210	0.43	0.1452	0.0015	7.1268	0.0931	0.3524	0.0035	2300	17	2127	12	1946	17	91%
-44	266.3	264	713	0.37	0.1103	0.0010	4.9246	0.0457	0.3202	0.0017	1806	16	1806	8	1791	8	99%
-45	161.9	170	312	0.55	0.1391	0.0013	8.2752	0.0886	0.4270	0.0031	2217	16	2262	10	2292	14	98%
-46	129.0	253	289	0.87	0.1203	0.0012	5.6090	0.0600	0.3350	0.0022	1961	23	1917	9	1863	10	97%
-47	211.5	374	438	0.85	0.1389	0.0014	7.5703	0.0909	0.3905	0.0031	2213	18	2181	11	2125	14	97%
-48	109.7	155	230	0.67	0.1260	0.0013	6.6323	0.0745	0.3783	0.0027	2044	18	2064	10	2068	12	99%
-49	173.7	177	327	0.54	0.1434	0.0013	8.7362	0.0925	0.4378	0.0031	2269	15	2311	10	2341	14	98%
-50	137.0	125	343	0.36	0.1169	0.0011	5.4973	0.0531	0.3382	0.0019	1910	18	1900	8	1878	9	98%
-51	215.8	177	347	0.51	0.1799	0.0016	12.2556	0.1307	0.4904	0.0041	2654	14	2624	10	2573	18	98%
-52	98.4	41.0	157	0.26	0.1785	0.0017	12.9855	0.1377	0.5232	0.0036	2639	11	2679	10	2713	15	98%
-53	48.7	68.7	120	0.57	0.1068	0.0013	4.8869	0.0608	0.3302	0.0027	1746	22	1800	10	1839	13	97%
-54	106.4	109	195	0.56	0.1406	0.0015	8.4237	0.0995	0.4313	0.0031	2236	19	2278	11	2312	14	98%
-55	134.8	120	308	0.39	0.1266	0.0013	6.5019	0.0767	0.3693	0.0027	2052	19	2046	10	2026	13	99%
-56	73.4	196	140	1.40	0.1222	0.0014	5.9134	0.0683	0.3483	0.0022	1989	20	1963	10	1926	10	98%
-57	62.0	70.0	119	0.59	0.1379	0.0014	7.9104	0.0866	0.4133	0.0028	2211	17	2221	10	2230	13	99%
-58	36.1	69.7	74.7	0.93	0.1208	0.0016	6.0204	0.0861	0.3598	0.0031	1969	23	1979	12	1981	15	99%
-59	82.1	263	167	1.58	0.1116	0.0013	5.0164	0.0616	0.3236	0.0023	1828	21	1822	10	1807	11	99%
-60	187.0	197	354	0.56	0.1432	0.0015	8.3718	0.0911	0.4207	0.0027	2266	18	2272	10	2264	12	99%
-61	49.4	77.2	82.9	0.93	0.1454	0.0019	8.8411	0.1230	0.4378	0.0035	2294	23	2322	13	2341	16	99%
-62	123.4	92.1	250	0.37	0.1429	0.0015	8.1120	0.0905	0.4081	0.0025	2263	19	2244	10	2206	12	98%
-63	215.1	194	431	0.45	0.1451	0.0014	8.2793	0.0852	0.4102	0.0023	2289	17	2262	9	2216	10	97%
-64	133.9	124	299	0.42	0.1377	0.0014	7.0855	0.0792	0.3696	0.0026	2198	18	2122	10	2028	12	95%
-65	160.0	132	332	0.40	0.1434	0.0014	7.9348	0.0791	0.3978	0.0024	2269	17	2224	9	2159	11	97%
-66	79.1	70.6	174	0.41	0.1253	0.0014	6.7131	0.0808	0.3852	0.0028	2035	20	2074	11	2101	13	98%
-67	62.0	61.8	109	0.57	0.1456	0.0017	9.2008	0.1131	0.4555	0.0035	2295	20	2358	11	2420	16	97%
-68	63.2	77.5	159	0.49	0.1106	0.0014	5.2508	0.0704	0.3418	0.0027	1810	23	1861	11	1895	13	98%
-69	123.9	94.3	238	0.40	0.1459	0.0017	8.7938	0.1075	0.4335	0.0030	2298	19	2317	11	2321	13	99%
-70	151.1	340	302	1.13	0.1213	0.0013	6.1160	0.0688	0.3626	0.0024	1976	14	1993	10	1994	11	99%
-71	63.0	75.0	117	0.64	0.1443	0.0016	8.6918	0.0966	0.4329	0.0027	2279	19	2306	10	2319	12	99%

续表 1

Continued Table 1

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续表 1

Continued Table 1

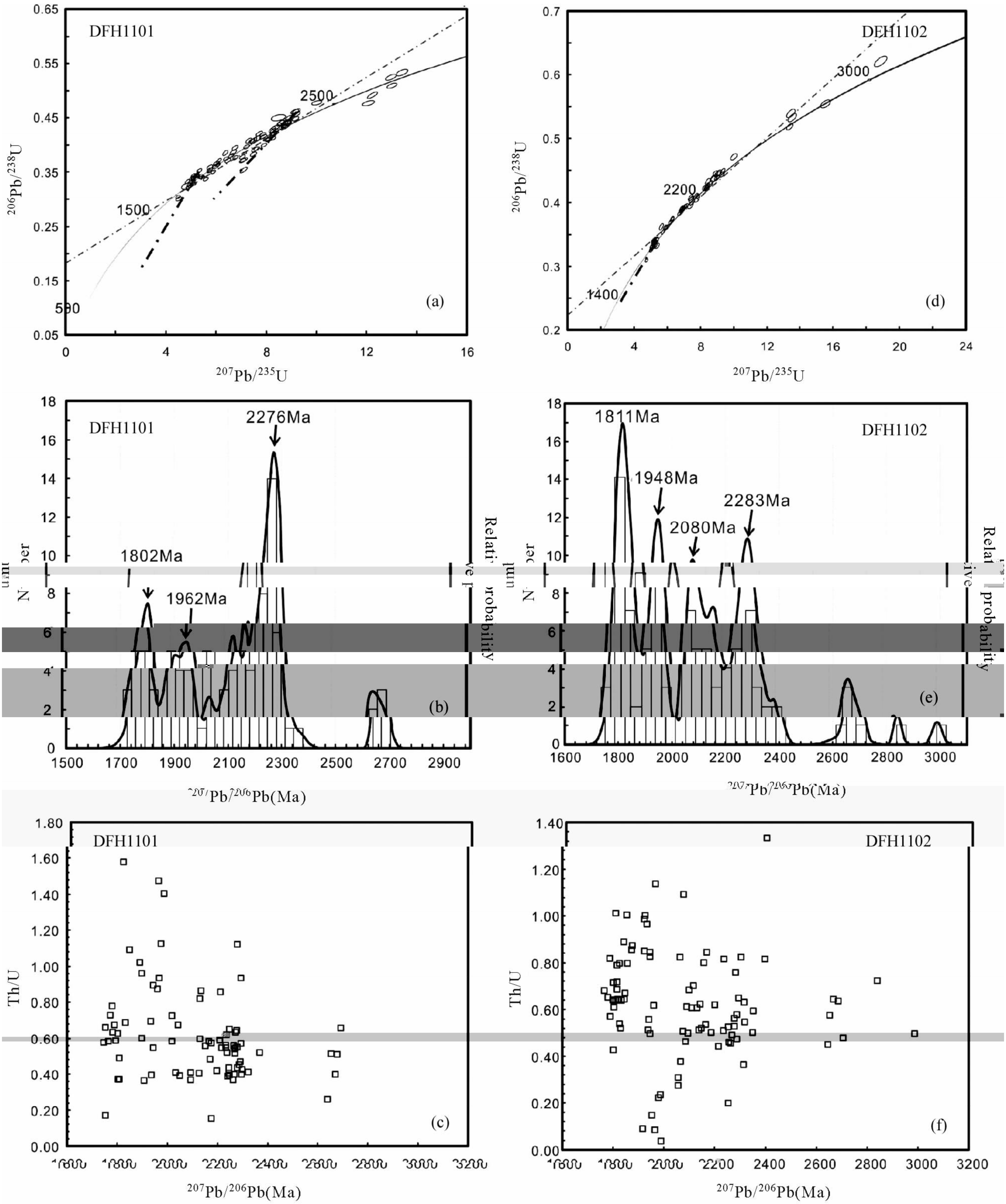
	×10⁻⁶			Th/U							Ma						
	Pb	Th	U		$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ	$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ	
-23	35.9	58.6	90.3	0.65	0.1089	0.0014	4.8011	0.0596	0.3184	0.0022	1781	23	1785	10	1782	11	99%
-24	124.4	140	328	0.42	0.1102	0.0011	4.8986	0.0548	0.3199	0.0021	1803	19	1802	9	1789	10	99%
-25	47.3	63.4	83.8	0.76	0.1447	0.0016	8.8049	0.1078	0.4384	0.0033	2284	19	2318	11	2343	15	98%
-26	251	503	461	1.09	0.1285	0.0011	7.0057	0.0682	0.3922	0.0024	2080	16	2112	9	2133	11	99%
-27	264.8	149	630	0.24	0.1221	0.0010	6.3192	0.0613	0.3724	0.0023	1987	15	2021	9	2041	11	99%
-28	115.3	209	253	0.83	0.1194	0.0011	5.8358	0.0601	0.3521	0.0022	1947	17	1952	9	1945	11	99%
-29	55.2	102	120	0.85	0.1178	0.0013	5.7559	0.0622	0.3521	0.0020	1924	19	1940	9	1945	10	99%
-30	136.7	271	317	0.85	0.1146	0.0012	5.2842	0.0547	0.3325	0.0020	1873	18	1866	9	1850	10	99%
-31	30.9	60.8	69.6	0.87	0.1146	0.0016	5.2778	0.0815	0.3321	0.0029	1876	26	1865	13	1849	14	99%
-32	23.08	50.6	50.6	1.00	0.1181	0.0018	5.4172	0.0837	0.3324	0.0028	1928	27	1888	13	1850	14	97%
-33	90.2	114	187	0.61	0.1295	0.0013	7.0000	0.0758	0.3890	0.0027	2092	18	2111	10	2118	13	99%
-34	42.1	58.7	71.3	0.82	0.1465	0.0016	9.0346	0.1112	0.4441	0.0031	2305	19	2342	11	2369	14	98%
-35	71.6	158	140	1.14	0.1207	0.0013	6.1774	0.0706	0.3686	0.0027	1969	20	2001	10	2023	13	98%
-36	22.71	23.3	45.7	0.51	0.1330	0.0018	7.4644	0.0996	0.4056	0.0033	2139	23	2169	12	2195	15	98%
-37	104.1	91.0	198	0.46	0.1424	0.0015	8.4429	0.0923	0.4268	0.0026	2257	19	2280	10	2291	12	99%
-38	82.6	72.3	159	0.45	0.1431	0.0017	8.4088	0.0993	0.4223	0.0028	2265	21	2276	11	2271	12	99%
-39	24.67	22.2	50.1	0.44	0.1391	0.0019	7.8226	0.1091	0.4057	0.0034	2216	24	2211	13	2195	16	99%
-40	70.6	86.8	143	0.61	0.1308	0.0014	7.1540	0.0789	0.3937	0.0026	2109	14	2131	10	2140	12	99%
-41	106.1	115	227	0.51	0.1283	0.0013	6.9709	0.0784	0.3906	0.0028	2076	18	2108	10	2126	13	99%
-42	63.38	14.7	165	0.09	0.1173	0.0012	5.7424	0.0639	0.3532	0.0024	1917	23	1938	10	1950	11	99%
-43	61.7	62.6	112	0.56	0.1443	0.0016	8.9434	0.1008	0.4460	0.0029	2279	19	2332	10	2378	13	98%
-44	70.20	15.1	179	0.08	0.1200	0.0013	6.0008	0.0692	0.3605	0.0026	1967	19	1976	10	1984	12	99%
-45	33.0	74.6	74.4	1.00	0.1134	0.0015	5.2027	0.0722	0.3307	0.0026	1855	24	1853	12	1842	12	99%
-46	142.31	13.1	354	0.04	0.1222	0.0013	6.3090	0.0731	0.3724	0.0026	1991	19	2020	10	2041	12	98%
-47	139.7	181	338	0.54	0.1115	0.0012	5.2756	0.0639	0.3409	0.0026	1825	25	1865	10	1891	12	98%
-48	83.7	82.5	179	0.46	0.1291	0.0014	6.9444	0.0832	0.3890	0.0028	2087	14	2104	11	2118	13	99%
-49	37.6	80.0	83.1	0.96	0.1142	0.0015	5.3632	0.0736	0.3401	0.0028	1933	24	1879	12	1887	13	99%
-50	79.5	72.0	143	0.50	0.1502	0.0014	9.3526	0.0946	0.4493	0.0029	2350	16	2373	9	2392	13	99%
-51	90.4	65.8	137	0.48	0.1860	0.0018	13.3917	0.1384	0.5196	0.0033	2706	17	2708	10	2697	14	99%
-52	76.6	135	197	0.68	0.1110	0.0012	4.7530	0.0564	0.3088	0.0019	1817	20	1777	10	1735	10	97%
-53	69.2	47.5	130	0.36	0.1472	0.0017	9.0958	0.1100	0.4458	0.0032	2314	19	2348	11	2377	14	98%
-54	57.6	107	136	0.79	0.1110	0.0014	5.0751	0.0666	0.3306	0.0023	1817	24	1832	11	1841	11	99%
-55	42.7	82.5	62.0	1.33	0.1541	0.0019	10.0469	0.1300	0.4716	0.0035	2392	21	2439	12	2490	16	97%
-56	50.9	61.0	98.5	0.62	0.1380	0.0016	7.8258	0.0915	0.4092	0.0027	2202	19	2211	11	2211	12	99%
-57	57.0	118	133	0.89	0.1127	0.0013	5.0735	0.0603	0.3259	0.0023	1843	21	1832	10	1819	11	99%
-58	71.5	75.5	151	0.50	0.1296	0.0014	7.0428	0.0849	0.3919	0.0029	2094	23	2117	11	2132	14	99%

续表 1

Continued Table 1

	×10^{-6}			Th/U							Ma						
	Pb	Th	U		^{207}Pb/^{206}Pb	1σ	^{207}Pb/^{235}U	1σ	^{206}Pb/^{238}U	1σ	^{207}Pb/^{206}Pb	1σ	^{207}Pb/^{235}U	1σ	^{206}Pb/^{238}U	1σ	
-59	31.92	19.8	40.0	0.50	0.2197	0.0026	18.8909	0.2486	0.6217	0.0055	2989	19	3036	13	3117	22	97%
-60	55.9	47.1	82.0	0.57	0.1800	0.0020	13.4778	0.1675	0.5401	0.0042	2653	18	2714	12	2784	17	97%
-61	26.04	43.5	61.0	0.71	0.1101	0.0016	5.1550	0.0768	0.3391	0.0027	1802	26	1845	13	1882	13	98%
-62	112.5	59.0	266	0.22	0.1217	0.0014	6.3109	0.0740	0.3741	0.0024	1981	53	2020	10	2048	11	98%
-63	47.2	55.3	85.2	0.65	0.1457	0.0019	8.8067	0.1194	0.4369	0.0033	2295	22	2318	12	2337	15	99%
-64	76.7	119	185	0.64	0.1100	0.0012	5.1465	0.0640	0.3371	0.0025	1799	16	1844	11	1873	12	98%
-65	44.3	70.9	106	0.67	0.1129	0.0014	5.2148	0.0658	0.3337	0.0023	1847	23	1855	11	1856	11	99%
-66	29.14	52.5	65.9	0.80	0.1116	0.0016	5.2541	0.0746	0.3412	0.0024	1825	26	1861	12	1892	12	98%
-67	63.2	128	130	0.99	0.1179	0.0014	5.8883	0.0706	0.3604	0.0025	1925	20	1960	10	1984	12	98%
-68	51.6	65.7	126	0.52	0.1120	0.0014	5.2242	0.0701	0.3365	0.0025	1832	23	1857	11	1870	12	99%
-69	86.1	82.9	115	0.72	0.2020	0.0024	15.5602	0.1927	0.5550	0.0039	2842	14	2850	12	2846	16	99%
-70	46.0	42.0	66.2	0.64	0.1836	0.0022	13.5549	0.1696	0.5334	0.0044	2687	20	2719	12	2756	19	98%
-71	59.9	85.4	105	0.81	0.1408	0.0016	8.4530	0.1001	0.4327	0.0031	2237	20	2281	11	2318	14	98%
-72	54.9	92.8	130	0.72	0.1110	0.0013	5.1143	0.0623	0.3320	0.0023	1817	21	1838	10	1848	11	99%
-73	19.44	20.6	35.7	0.58	0.1450	0.0021	8.8198	0.1403	0.4382	0.0042	2289	24	2320	15	2343	19	99%
-74	43.9	62.1	96.8	0.64	0.1129	0.0014	5.6604	0.0775	0.3616	0.0032	1847	18	1925	12	1990	15	96%
-75	52.0	69.6	99.6	0.70	0.1313	0.0015	7.4376	0.0966	0.4073	0.0032	2117	21	2166	12	2202	15	98%
-76	51.9	81.3	128	0.64	0.1115	0.0014	5.0472	0.0683	0.3250	0.0023	1833	18	1827	11	1814	11	99%
-77	135.6	54.7	276	0.20	0.1420	0.0016	8.3715	0.0974	0.4228	0.0028	2254	20	2272	11	2273	13	99%
-78	48.6	53.1	99.1	0.54	0.1351	0.0018	7.4327	0.1073	0.3946	0.0031	2165	23	2165	13	2144	14	99%
-79	79.1	93.5	154	0.61	0.1324	0.0015	7.4413	0.0910	0.4038	0.0029	2131	20	2166	11	2187	13	99%
-80	105.5	131	236	0.56	0.1191	0.0012	5.9883	0.0654	0.3611	0.0024	1943	19	1974	10	1987	11	99%
-81	173.4	174	320	0.54	0.1476	0.0014	9.0175	0.0919	0.4386	0.0028	2318	21	2340	9	2344	12	99%
-82	150.7	227	284	0.80	0.1346	0.0013	7.4881	0.0761	0.3989	0.0024	2159	17	2172	9	2164	11	99%
-83	160.0	213	347	0.62	0.1203	0.0012	6.0871	0.0616	0.3630	0.0020	1961	23	1988	9	1996	10	99%
-84	54.2	84.6	132	0.64	0.1113	0.0014	5.0491	0.0645	0.3255	0.0022	1820	22	1828	11	1816	11	99%
-85	30.4	56.5	70.9	0.80	0.1136	0.0018	5.3533	0.0895	0.3403	0.0033	1858	29	1877	14	1888	16	99%
-86	111.2	68.5	250	0.27	0.1270	0.0014	6.7727	0.0780	0.3827	0.0025	2057	18	2082	10	2089	12	99%
-87	80.5	84.9	143	0.59	0.1507	0.0016	9.3012	0.1041	0.4435	0.0029	2353	19	2368	10	2366	13	99%
-88	44.90	36.6	97.4	0.38	0.1276	0.0015	6.9153	0.0855	0.3895	0.0028	2066	16	2101	11	2121	13	99%
-89	86.3	134	159	0.84	0.1355	0.0014	7.7422	0.0859	0.4104	0.0029	2170	17	2202	10	2217	13	99%
-90	149.3	102	331	0.31	0.1271	0.0013	6.8407	0.0719	0.3864	0.0023	2058	18	2091	9	2106	11	99%
-91	58.7	53.0	112	0.47	0.1448	0.0016	8.6416	0.1050	0.4291	0.0031	2287	19	2301	11	2302	14	99%
-92	39.6	60.6	95.7	0.63	0.1103	0.0015	5.1442	0.0720	0.3354	0.0024	1806	24	1843	12	1865	12	98%
-93	61.9	62.3	119	0.53	0.1415	0.0018	8.3089	0.1079	0.4230	0.0029	2256	50	2265	12	2274	13	99%

Pb



7 U-Pb ^{207}Pb/^{206}Pb Th/U-^{207}Pb/^{206}Pb

Fig. 7 Plot of U-Pb concordant curve ^{207}Pb/^{206}Pb age frequency and Th/U-^{207}Pb/^{206}Pb age diagram of the detrital zircons from tuff and breccia of the Yinachang deposit

表 2　迤纳厂矿床中黄铜矿的 Re-Os 同位素组成

Table 2　Re-Os isotope compositions for chalcopyrite from the Yinachang deposit

	^{187}Re $\times10^{-9}$	1σ	^{187}Os $\times10^{-9}$	1σ	Re $\times10^{-9}$	1σ	Os $\times10^{-9}$	1σ	Ma	1σ
YNC1006	562.306	16.269	16.881	0.314	898.253	25.989	0.023	0.006	1732	23
10YNC-40	161.659	2.145	4.455	0.061	258.242	3.426	0.017	0.001	1638	22
YNC1010	4.615	0.108	0.118	0.003	7.373	0.172	0.003	0.000	1719	20
10YNC-32	12.859	0.300	0.366	0.004	20.541	0.480	0.004	0.000	1690	20
10YNC-41	246.010	30.390	6.836	0.079	392.988	48.547	0.005	0.001	1651	19
YNC1112	4.388	0.149	0.073	0.005	7.010	0.239	0.002	0.000	1687	19

5

5.1　锆石 U-Pb 年代学

LA-ICP-MS U-Pb
1 6 CL
7 U-Pb $^{207}Pb/$
^{206}Pb Th/U-$^{207}Pb/^{206}Pb$
DFH1101 2000
84 95%
$^{207}Pb/^{206}Pb$ 1746 ± 22Ma $^{207}Pb/^{206}Pb$
2694 ± 16Ma 5 2500Ma
1.75 ~ 1.85Ga
1.90 ~ 2.00Ga 2.20 ~ 2.35Ga
$^{207}Pb/^{206}Pb$ 1796 ± 15Ma n
= 16 MSWD = 1.5 2262 ± 12Ma n = 34 MSWD = 3.5
1800Ma 1960Ma 2270Ma
7b CL
6 Th/U 0.1
0.4 ~ 1.0 7c
DFH1102 2500
93
95% $^{207}Pb/^{206}Pb$ 1767 ± 27Ma
$^{207}Pb/^{206}Pb$ 2989 ± 19Ma 7
2500Ma 1.75
~ 1.88Ga 1.90 ~ 2.00Ga 2.02 ~ 2.20Ga 2.30 ~ 2.40Ga
$^{207}Pb/^{206}Pb$
1796 ± 9Ma n = 19 MSWD = 0.71
1800Ma 1950Ma 2080Ma 2280Ma
7e CL
6 Th/U 0.2 0.4
~ 1.0 7f
U-Pb
1750 ~ 2300 Ma 1750Ma
CL Th/U

5.2　黄铜矿 Re-Os 同位素年代学

Fe-Cu-REE 6 Re-Os
2 Re 7.01 × 10^{-9} ~
898.25 × 10^{-9} Os 0.002 × 10^{-9} ~
0.023 × 10^{-9} ^{187}Os Os 97%
$^{187}Re/^{188}Os$ > 11000 Os
Os
^{187}Re-^{187}Os $^{187}Re/^{188}Os$-$^{187}Os/^{188}Os$ Stein
et al. 2000 ISOPLOT Ludwig 2001
^{187}Re-^{187}Os 1690 ± 99Ma MSWD =
9.0 8a 1685 ± 37Ma MSWD = 3.0
8b

5.3　矿石的稀土地球化学特征

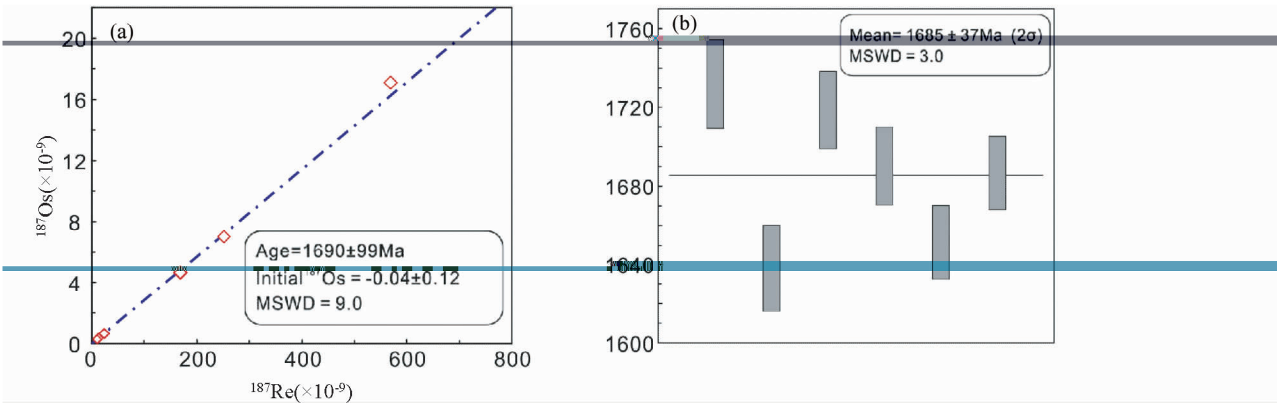
3 9
YNC1004
116 × 10^{-6} 665 × 10^{-6} ~ 2460 × 10^{-6}
$(La/Yb)_N$ 11.1 ~ 74.1 $(La/Sm)_N$ 3.1 ~ 8.5 $(Gd/Yb)_N$
1.8 ~ 5.0 LREE/HREE 6.9 ~ 26.6
δEu = 1.95 ~ 4.06 δCe = 0.87 ~ 1.01
3 9a
∑REE = 581 ×
10^{-6} ~ 10736 × 10^{-6}
11000 × 10^{-6} $(La/Yb)_N$ = 5.51
~ 31.9 LREE/HREE = 4.3 ~ 13.5
$(La/Sm)_N$ = 1.7 ~ 4.1 (Gd/
Yb)$_N$ = 2.0 ~ 4.5 δEu =
0.99 ~ 1.49 δCe = 0.93 ~ 1.29 3
9b

表 3 迤纳厂矿床中矿石和围岩的稀土元素含量(×10^{-6}) 及特征值

Table 3 Rare earth elements REE contents ×10^{-6} of ores and wall-rock form the Yinachang deposit

	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	∑REE	δEu	δCe	La/Yb_N	La/Sm_N	Gd/Yb_N	LREE/HREE
10YNC-31	670	1050	108	340	54.8	29	37.9	5.38	27.4	4.46	10	1.36	6.2	0.5	2345	1.95	0.94	72.86	7.69	4.93	24.16
10YNC-41	584	983	101	320	53.1	30.9	38.9	6.07	32.1	5.92	14.2	2.04	9.7	0.94	2182	2.08	0.97	40.59	6.92	3.24	18.86
DFH1111	264	421	41.1	128.5	19.5	11.8	12.5	1.63	8.9	1.61	4.4	0.87	5.3	0.57	922	2.31	0.97	33.58	8.52	1.90	24.76
DFH1112	609	961	97.9	319	52.1	44.4	42.1	6	31.2	6.02	14.3	1.78	8.9	0.73	2194	2.90	0.95	46.13	7.35	3.82	18.76
YNC1003	186	340	47.2	179	38.1	26.4	36.8	6.09	35	6.95	17.9	2.12	11.3	1.13	934	2.16	0.87	11.10	3.07	2.63	6.96
YNC1004	31.2	53.1	5.05	17.1	2.6	3.09	2.08	0.23	0.975	0.154	0.404	0.0453	0.284	0.033	116	4.06	1.02	74.07	7.55	5.92	26.63
YNC1011	144	228	21.4	74.5	14.6	19.8	15.9	2.88	16.7	3.74	9.87	1.33	6.93	0.783	805	3.97	0.99	14.01	6.20	1.85	8.64
YNC1015	217	335	29.9	102	18.3	24.1	20.9	3.86	22.8	5.38	13.3	1.73	9.54	1.08	560	3.77	1.00	15.34	7.46	1.78	9.23
YNC1006	129	279	31.6	124	27.6	10.3	29.5	5.38	31.9	7.09	18.5	2.34	12	1.18	709	1.10	1.05	7.25	2.94	1.98	5.58
YNC1007	125	249	26.8	99.7	19.5	7.6	19.3	2.98	15.2	2.96	7.24	0.853	4.58	0.477	581	1.20	1.04	18.40	4.03	3.41	9.84
YNC1008	169	322	41.2	158	25.3	8.55	20.4	3.1	14.9	3.31	8.54	1.17	6.48	0.747	783	1.15	0.93	17.58	4.20	2.55	12.35
YNC1009	2180	4320	525	1890	374	125	320	52.8	320	68.3	159.5	20.7	88.2	8.2	10452	1.11	0.97	16.66	3.67	2.93	9.07
YNC1010	251	640	90.9	370	93.7	45.8	93.9	17.4	104	21.4	51.6	5.89	26.5	2.45	6223	1.49	1.02	6.39	1.69	2.86	4.61
YNC1012	382	978	120	572	130	60.7	147	26.9	163	36.3	88.4	10.3	46.6	4.36	10736	1.34	1.10	5.53	1.85	2.54	4.29
YNC1013	356	1111	121	496	102	43.3	97.9	17.7	98.6	20.1	47.3	5.31	23.8	2.28	4802	1.32	1.29	10.08	2.20	3.32	7.12
YNC1014	1060	2423	279	1320	271	87.6	268	43.8	235	48.2	112	12.7	57.9	5.17	2766	0.99	1.07	12.34	2.46	3.73	6.95
10YNC-30	2350	4630	558	1970	361	126	274	40.6	223	43.3	94.1	12.3	49.6	4.35	2542	1.22	0.97	31.94	4.09	4.46	13.48
10YNC-32	1035	2040	243	868	162.5	51.7	136	21.8	118	24.7	57.8	7.23	33	2.97	1815	1.06	0.98	21.15	4.01	3.33	10.96
YNC1001	47	91.7	9.08	31.9	6.13	4.59	5.16	0.8	4.5	0.968	2.69	0.367	2.24	0.309	207	2.49	1.07	14.15	4.82	1.86	11.18
YNC1002	71.1	125	11.5	36.7	6.33	4.49	5.58	0.758	3.39	0.744	2.06	0.307	2	0.274	270	2.31	1.05	23.97	7.07	2.25	16.89

∑REE δEu = Eu/ Sm × Gd $^{1/2}$ δCe = Ce/ La × Pr $^{1/2}$ LREE/HREE = ∑ La – Sm / ∑ Gd – Lu . Boynton 1984



8 Re-Os a b

Fig. 8 Isochrone age diagram a and weighted average of model age b of Re-Os isotope for chalcopyrite of the Yinachang deposit

∑REE = 207 ×10^{-6} ~270×10^{-6} $(La/Yb)_N$ 14.1 ~ 23.9 $(La/Sm)_N$ 4.8 ~7.1 LREE/HREE 11.2 ~ 16.9 δEu =2.31 ~2.50 δCe = 1.1 3 9c

6

6.1 迤纳厂组的沉积时限和归属

1954

1990

1993 1995

Zhang *et al.* 2006 Greentree and Li 2008 Zhao *et al.* 2010

LA-ICP-MS U-Pb

DFH1101 1746 ± 22Ma U 120×10^{-6} Th 68.7×10^{-6} Th/U 0.57

DFH1102 $^{207}Pb/^{206}Pb$ 1767 ± 27Ma U 91×10^{-6} Th 62×10^{-6} Th/U 0.68

$^{207}Pb/^{206}Pb$ 1750Ma

1750Ma

1780Ma U-Pb 1742 ± 13Ma Zhao *et al.* 2010

U-Pb 1690±32Ma Zhao *et al.* 2010

1.7Ga

U-Pb 1711 ±4Ma

2012 U-Pb 1.7Ga

2008 Greentree and Li 2008 Zhao and Zhou 2011 1.7Ga

U-Pb 1695 ±20Ma 2009

1710±8Ma U-Pb 2011

~1800Ma ~1950Ma ~2080Ma ~2280Ma 2.5Ga

6.2 迤纳厂 Fe-Cu-REE 矿床成矿年代学限制

-

Li *et al.* 2002 Zhao and Zhou
2011

2004a Fe-Cu-REE
^{40}Ar-^{39}Ar 784.25 ±0.95Ma
783.93±8.59Ma 2005
Sm-Nd 1539
±40Ma 1617±100Ma

-
Rb-Sr
845±2Ma 1994
Pb-Pb 888Ma 2006
Re-Os 928~1005Ma 2003
1086±8Ma Chen and Zhou 2012
-
2002
^{40}Ar-^{39}Ar 1470Ma 810~
770Ma Qiu *et al.* 2002
^{40}Ar-^{39}Ar
780~700Ma
1470Ma -
2004b
^{40}Ar-^{39}Ar
768.43±0.58Ma 770±5Ma
Fe-Cu
800Ma
^{40}Ar-^{39}Ar Rb-Sr
^{40}Ar-^{39}Ar 350℃ Jenkin *et al.* 2001 Rb-Sr Rb
Rb-Sr 2011
Re-Os

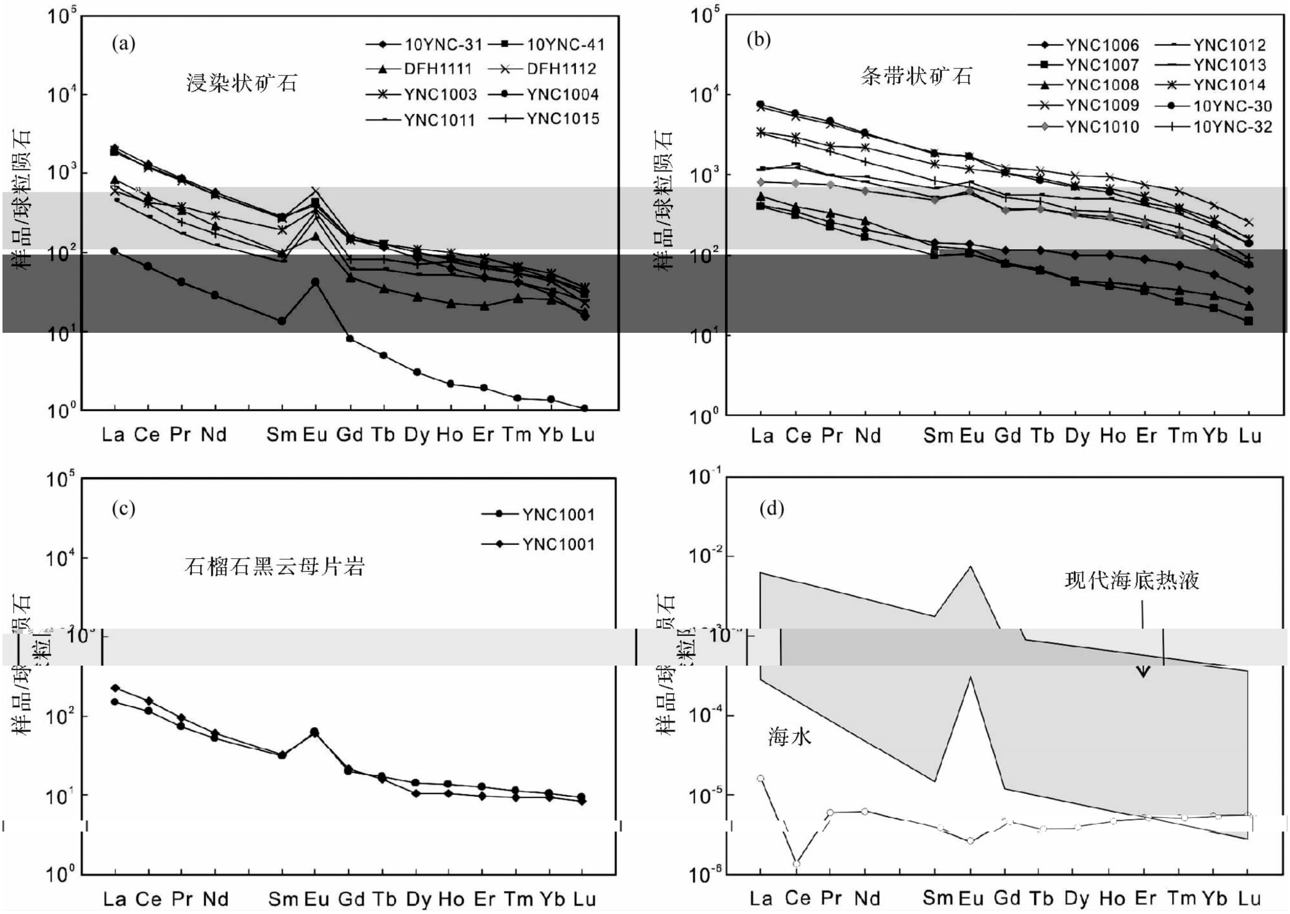
Stein *et al.* 1998 6
Re-Os 1690±99Ma
1685±37Ma
2
1690Ma 784Ma
^{40}Ar-^{39}Ar
1.7Ga

-
Fe-Cu-REE

6.3 迤纳厂矿床的稀土元素特征及成因的初步认识

Michard and Albarède 1986
Michard 1989 Klinkhammer *et al.* 1994 Craddock *et al.* 2010
Klinkhammer *et al.* 1994
9d

Graf
1977 Lottermoser 1989 1992 “



9 a b c

d Craddock *et al.* 2010 Elderfield and Greaves 1982

Boynton 1984

Fig. 9 Chondrite-normalized REE patterns for disseminated ores a banded ores b and garnet biotite schist c of the Yinachang deposit

REE patterns for submarine hydrothermal fluids after Craddock *et al.* 2010 REE pattern for seawater after Elderfield and Greaves 1982 chondrite-normalizing values after Boynton 1984

IOCG

7

1.7Ga -

1.7Ga Columbia

Rogers and Santosh 2002

Zhao *et al.* 2002

-

Columbia Zhao and Zhou 2011 Wang *et al.* 2012 Yu *et al.* 2012

1.7Ga

- Fe-Cu

1

LA-ICP-MS U-Pb 1750Ma

2 Fe-Cu-REE Re-Os

1690 ± 99Ma 1.7Ga

3

-

致谢 209

U-Pb Re-Os

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